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ORIGINAL PAPER

Electrical-Model of ADITYA-U Tokamak

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Abstract: An Electrical-Model is developed for ADITYA-U Tokamak to study the generation of different shapes and duration of LVs out of the total available flux, which is 0.6 Vs in positive convertor supply. Loop voltage (LV) is required to be controlled during plasma discharge to optimize and predict the breakdown of plasma, proper impurity burn-through time, plasma current magnitude and duration of the plasma as per the experimental requirement. Loop voltage waveform is governed by selecting different magnitudes of resistance values, switching time and duration of external resistance in the wave shaping primary circuit. Loop voltage control system has been modelled using simulation code (Electrical-Model). Same results have been validated with the modelling of ohmic wave shaping circuit in MATLAB-Simulink. Temporal profile of loop voltage has been incorporated for ADITYA-U Tokamak for several plasma discharges, and detailed observations and results are presented in the paper.

Keywords: Loop voltage; ADITYA-U Tokamak; Transformer model; Plasma

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1. Introduction

Nuclear fusion is one of the most promising options for generating clean and abundant energy in the future. Fusion is the process that powers the sun and all other stars, where atomic nuclei fuse together and release energy. To overcome the repulsive Coulomb forces, the fuel gas must be heated to temperatures over 100 million degree Celsius [1], which becomes plasma at this temperature. Plasma is a collection of ions, electrons and neutral particles. It exhibits collective behaviour as well as quasi-neutrality. To obtain energy from fusion, this highly heated plasma, with sufficient density (n), needs to be confined for sufficiently long time. The figure of merit is given by the ignition condition, which says that for ignition, the triple product of $nT\tau_E > 5 \times 10^{21}$ m^{-3} keVs [2]. Magnetic fields are used to confine this highly heated plasma, and based on different configurations of the confining magnetic fields, different devices are developed and studied. One of the most researched and advanced devices capable of achieving nuclear fusion is known as tokamak.

Tokamak is the most favourable candidate for magnetic confinement system and it is the basis for the design of future fusion reactors. Tokamak is an electro-mechanical device with different magnetic coils to initiate, confine and control the stability of the plasma. Generally, the tokamaks are operated in pulsed power mode. Conventional tokamak consists of a toroidal chamber (vacuum vessel), central solenoid, toroidal magnetic field (TF) coils, poloidal field (PF) coils and vertical field (BV) coils as shown in Fig. 1. Toroidal magnetic field is the main confining field, whereas the vertical field or the poloidal magnetic fields are used to overcome the radial outward forces (the hoop force, the tyre–tube force and the 1/R force) that lead to radial outward displacement of plasma [3].

Tokamak's basic working principal is based on solenoid which works as a primary circuit of the transformer and a single-turn plasma column, which works as its secondary circuit [4]. A time-varying current in the primary central solenoid generates a voltage in the plasma column ring, called 'loop voltage (LV)', which breaks the neutral gas into ions and electron, and drives current through the

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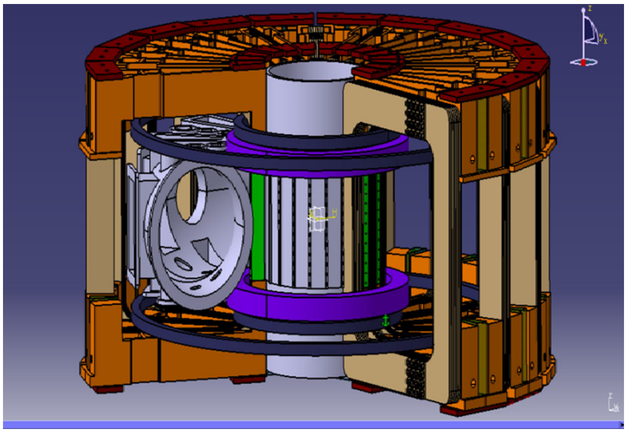

Fig. 1 Schematic of ADITYA-U Tokamak—a magnetic confinement device [6]

plasma. This plasma current has two important roles in tokamak: first, it produces a poloidal magnetic field, which is required for plasma equilibrium [5], and second, it heats up the plasma. This type of heating is known as 'ohmic heating' and is the main source of heating in ADITYA-U Tokamak.

Generally, as the gas breakdown needs higher voltages, whereas driving the current in the plasma requires much less voltage, the magnitude of loop voltage (LV) is required to be controlled during plasma discharge to optimize and predict the breakdown of plasma, proper impurity burn-through time and achievement of plasma current flat-top. Peak value of loop voltage is decided to achieve breakdown of gas, after the breakdown of the gas the loop voltage is reduced to achieve desired current ramp-up phase and it is further reduced to achieve and maintain the plasma current at flat-top. Hence, proper time profiling of the LV is required in order to obtain a normal tokamak plasma discharge.

When the plasma acts as a load in the secondary, the LV comprises of a resistive (I_pR) part and an inductive $L\frac{dI_p}{dt}$ part, where inductive part can be further divided into internal (current profile-dependent) and external (machine's geometry-dependent) inductances, I_p, R and L denote the plasma current, plasma resistance and total inductance of plasma. Resistive part of loop voltage leads to ohmic heating ($\eta \propto T^{-3/2}$) in the tokamak and the inductive part becomes negligible when the plasma current IP remains constant at the flat-top. As mentioned in the above sentence, the resistivity of the plasma reduces with the temperature, and hence, after a certain temperature the efficiency of 'ohmic heating' reduces drastically and auxiliary heating techniques are required to heat the plasma at those temperatures. The magnetic coils producing the LV in tokamaks are designed in such a way that only the voltage remains present in the region where plasma is formed and confined and the magnitude of the time-varying magnetic fields due to the current in the primary coil should remain almost zero at some location inside that region known as 'null point'. The null point is crucial for neutral gas breakdown and plasma current ramp-up. However, due to the imperfection and asymmetry in the geometry of magnetic coils as well as their placements in the machine, the presence of unwanted magnetic fields (mainly the radial B_r and vertical B_z components), also known as error fields [7], leads to the contamination of the 'null point' and hence causes obstacle in gas breakdown and plasma current start-up.

Different models have been designed for different tokamak machines [4] to study and optimize the operation scenarios. In this paper, we present an Electrical-Model, developed for ADITYA-U Tokamak to study the generation of different shapes and duration of loop voltages out of the total available flux, which is 0.6 Vs in positive convertor supply. Temporal profile of current in ohmic transformer (OT) coil is modelled and benchmarked for all plasma and vacuum discharges with the measured temporal profiles of current. Loop voltage temporal waveform is obtained by selecting different magnitudes of resistance values, ignitron switching time and duration of external resistance in the wave shaping primary circuit. Loop voltage control system has been modelled named as 'Electrical-Model of ADITYA-U Tokamak', and the ohmic coil current and LV generated due to these currents have been obtained for various plasma discharges as well as for vacuum shots in which there is no plasma. Fairly good match of modelled results with experimentally measured data is observed with in the experimental tolerance. Further, the modelled results have been validated with those simulated through circuit in MATLAB-Simulink. Loop voltage for plasma shot and vacuum shot have been modelled in this paper to optimize the performance of the external power supply parameters.

The paper is organized as follows: Sect. 2 describes the ADITYA-U Tokamak system, ohmic transformer (OT) current simulation and validation of Electrical-Model with MATLAB-Simulink. Section 3 includes the model simulation results, and Sect. 4 concludes the paper.

2. ADITYA-U Tokamak modelling

2.1. ADITYA-U Tokamak

In this paper, we have carried out the Electrical-Modelling of ADITYA-U Tokamak. The ADITYA-U Tokamak is an air-core tokamak, with major radius $R0 = 75$ cm and minor radius $a = 25$ cm as shown in Fig. 2. According to Paschen curve [8], we need to have electric field inside the vacuum vessel to ionize the gas molecules and subsequent plasma

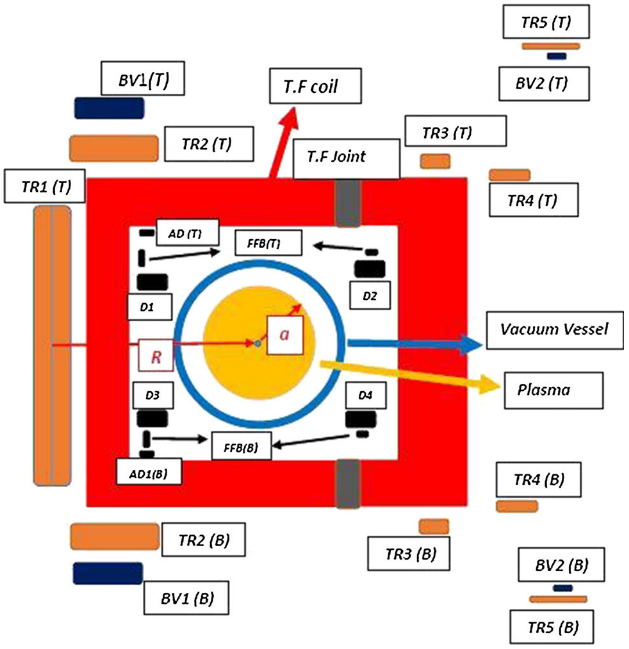

Fig. 2 Schematic of ADITYA-U Tokamak

production. As mentioned earlier, this electric field is produced by transformer action in tokamak with the plasma inside the vacuum vessel. In ADITYA-U Tokamak, there are nine coils in the primary side of the ohmic transformer, namely TR1, TR2 (T), TR2 (B), TR3 (T), TR3 (B), TR4 (T), TR4 (B), TR5 (T) and TR5 (B). All these coils are connected in series configuration with total 302 turns. TR1 is mainly responsible for producing the time-varying flux which produces the loop voltage (LV), and other eight auxiliary transformer coils are used in order to reduce the error fields inside the vacuum vessel and to have a good null location at a desired location inside the vacuum vessel [9]. The toroidal vacuum vessel is made up of two semi-tori electrically isolated with each other. Other magnetic coils include 20 numbers of TF coils, two sets of vertical magnetic field coils, three sets of divertor coils and two sets of fast feedback coils. The machine is operated with TF ~ 1.0–1.3 T. Again as mentioned in the previous section, apart from ionization, the LV drives the plasma current, which heats up the plasma column and leads to plasma temperature ~ 400 eV (Spitzer). This heating mechanism is known as ohmic heating. Besides ohmic heating, at present, the ADITYA-U Tokamak has provision of heating by launching electron cyclotron resonance (ECR) wave [10].

2.2. Tokamak start-up

A base vacuum pressure in the range of 2×10^{-9} to 6×10^{-9} Torr is maintained during the tokamak operation for the plasma discharges. Regular discharges are obtained in hydrogen gas, which is filled at a pressure range (0.8–2.0) $\times 10^{-4}$ Torr [7]. A filament is set for 20 A current and biased voltage 200 V to generate stray electrons inside the vacuum vessel for pre-ionization. Initially, a current in the primary of the transformer (OT transformer coils) is raised slowly and held constant at ~ 11 kA by the action of external power supply. At this point, a breaker is opened to discontinue the power supply connected to the transformer and brings in resistances while closing the circuit onto itself. The primary circuit current is driven towards zero from its maximum value ~ 11 kA through different resistances, assisted with different fast switches, switching resistances at different times. The transformer coupling (Fig. 3) between primary central solenoid and secondary plasma ring is accounted by mutual inductance, M_1. The total inductance of secondary plasma circuit is the addition of external and internal inductances of the plasma ring. External inductance primarily depends on geometrical parameter of plasma column ring, and internal inductance mainly depends on radial current profile present in the plasma. For this Electrical-Model, external and internal inductances of plasma are 1.001 µH and 0.5 µH, respectively, so total inductance of plasma ring is considered as a constant for ADITYA-U Tokamak.

Voltage across ohmic transformer (OT) coil is given by Eq. 1.

$$V_{\mathrm{pc}} = V_{\mathrm{ps}} - I_{\mathrm{pc}} R_{\mathrm{pc}} = L_{\mathrm{OT}} \frac{\mathrm{d}I_{\mathrm{pc}}}{\mathrm{d}t} \tag{1}$$

Here V_{pc} denotes the voltage across the primary coil (OT coil), and V_{ps}, I_{pc}, R_{pc} and L_{OT} are the applied power supply voltage, current in the primary coil, resistance of the primary circuit and self-inductance of primary circuit, respectively.

Induced voltage in single-turn loop (in vacuum) is given by Eq. 2.

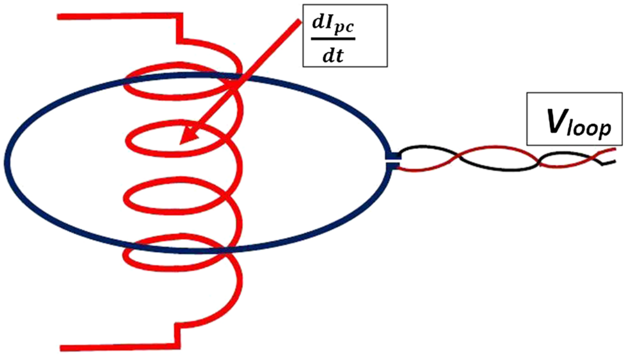

Fig. 3 Schematic of transformer action

$$LV_{\mathrm{vac}} = -M_1 \frac{\mathrm{d}I_{\mathrm{pc}}}{\mathrm{d}t} \qquad (2)$$

where LV_{vac} denotes the LV of vacuum discharge and M_1 is the mutual inductance between primary coil and single-turn loop; for ADITYA-U Tokamak, M_1 is 34.7 μH [9]. The electric field at the radius R_{o} is given by Eq. 3.

$$E = LV_{\mathrm{vac}}/2\pi R_{\mathrm{o}} \qquad (3)$$

where R_{o} is the major radius of the tokamak.

In a tokamak, the transformer primary circuit (central solenoid) plays a crucial role to ramp up the plasma current to its flat-top value. Operation of ohmic transformer current for the first phase (positive converter) is demonstrated by Electrical-Model. Time evolution of ohmic current is incorporated by choosing the resistance values of different magnitudes and switching action of different switches at different timings (Table 1) in the loop voltage generation circuit as shown in Fig. 4.

For ADITYA-U Tokamak, L_{OT} = 16.4 mH and R_{OT} = 90 mΩ

Table 1 OT wave shaping circuit parameters

Initial time (ms)	Resistance switching time (ms)	Resistance value (mΩ)
0	16	$R1$ = 720
16	28	$R2$ = 480
28	32	$R3$ = 120
32	–	R_{OT} = 90

$$I = I_0 \exp\left(-t/\tau\right), \quad \text{where } \tau = L_{\mathrm{OT}}/R_{\mathrm{total}} \qquad (4)$$

$$R_{\mathrm{total}} = R_{\mathrm{OT}} + R_{\mathrm{ext.}}\ (R1,\ R2,\ R3) \qquad (5)$$

To construct the primary coil current in Electrical-Model, an exponential decay equation has been used for different τ (L/R) and time slots. To construct total primary current (OT current), four sections of current have been constructed from 0 ms to 64 ms, as it can be estimated by Eqs. 4 and 5.

In ADITYA-U tokamak, plasma current generally evolves in the range of 50–300 ms, and after ~ 50 ms, plasma LV is forced to maintain at a constant value ~ 2 V to maintain the flat-top of plasma current.

Therefore, it becomes quite essential to study the shape of LV before ~ 60 ms that is why LV profiles of plasma parameters has been taken for 60 ms in this Electrical-Model. Also, time frame can be changed in the Electrical-Model as required.

High-magnitude current operation in ohmic transformer (OT) and vertical field (BV) coils would lead to a mutual flux coupling between these coils due to the closest installation at tokamak. Mutual flux coupling between the vertical field coils and ohmic transformer coils has been incorporated in terms of resistance and inductance values, as its becomes essential when both coils are mutually coupled with each other.

A DC converter (external current source) is used as a feedback network in the negative direction of primary coil current in addition to the pre-programmed current to maintain a finite value of LV during the flat-top region. External current given by Eq. 6 is started from initial phase, but its effect dominates after ignition of ignitron I3

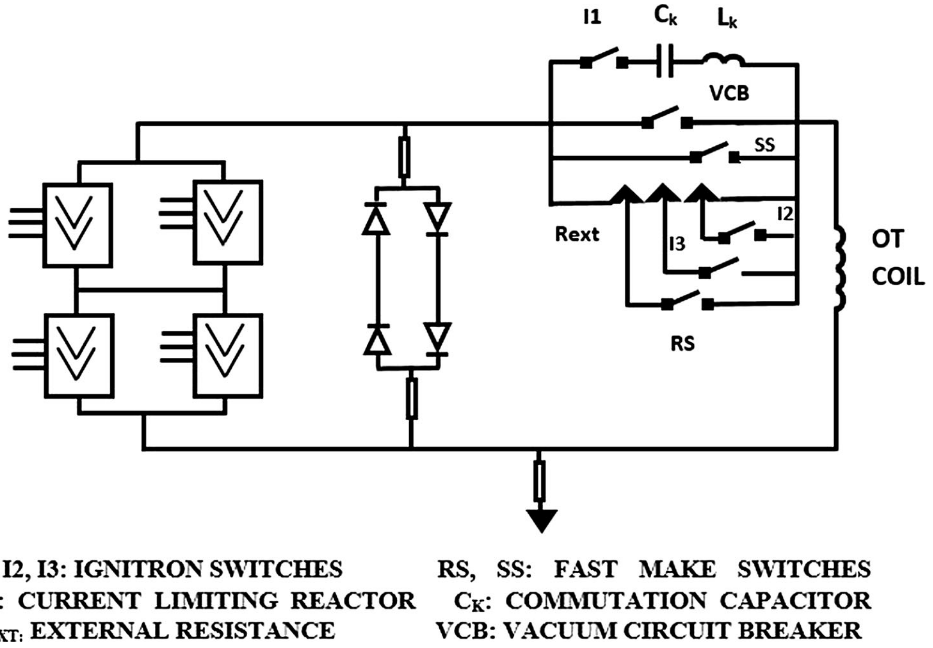
I1
Ck
Lk
VCB
SS
I2
Rext
I3
RS
OT COIL
I1, I2, I3: IGNITRON SWITCHES
RS, SS: FAST MAKE SWITCHES
LK: CURRENT LIMITING REACTOR
CK: COMMUTATION CAPACITOR
REXT: EXTERNAL RESISTANCE
VCB: VACUUM CIRCUIT BREAKER

Fig. 4 Loop voltage generation circuit

in primary circuit, because of its high decay time (τ). External current source can be altered in a desired manner. But for this model, this external current source has been taken similar for all the (plasma and vacuum discharges) loop voltages profiles.

Drop rate of OT current is maintained at 58 kA/s to generate the constant LV magnitudes ~ 2 V, and the external current source is used after 32 ms (third resistance switching time). External current is derived using simple *L*–*R* equivalent circuit for peak current magnitude and decay time constant (τ).

$$I_{\mathrm{ext}} = -I_{\mathrm{eo}} * (1 - \exp(-t/\tau_1)) \tag{6}$$

where decay time $\tau = \tau_1 = 35$ ms and $I_{\mathrm{eo}} = 3$ kA. Negative sign defined the external current direction opposite to OT current as shown in Fig. 5. Blue- and red-coloured lines in Fig. 6 denote OT current without the external source and with external current source, respectively. From the beginning of the third resistance switching, OT current without external source is used; after third resistance switching time, OT current with external source is used to maintain the ramp-down rate of OT current to maintain the constant LV.

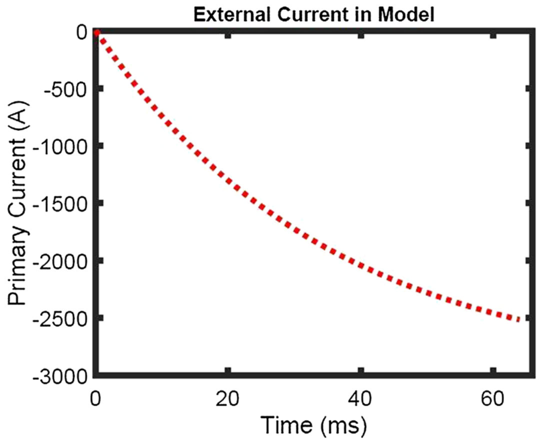

Fig. 5 External current in primary (OT) coil

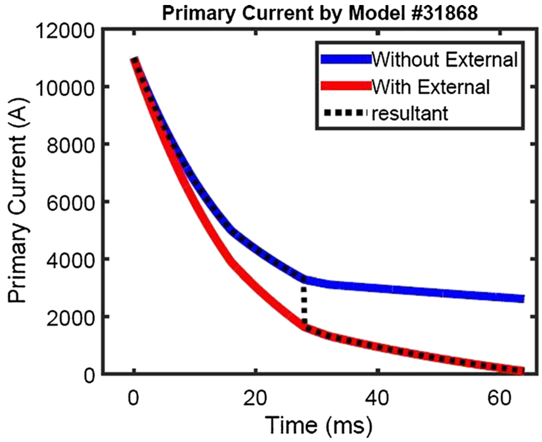

Fig. 6 Formulation of resultant OT current which is used in this model

The effect of external current source in OT current is shown in Fig. 6. Resultant OT current is used in this model.

2.3. Validation of Electrical-Model using MATLAB-Simulink

MATLAB-Simulink, a graphical block diagram tool with customizable set of block libraries, viz. resistor, inductor, time-controlled switch, etc., has been used to model and simulate the OT current. Validation of Electrical-Model with MATLAB-Simulink has been performed in order to cross-check the results obtained from the modelling. The complete electrical circuit of the wave shaping unit of the ohmic transformer has been replicated in MATLAB-Simulink to simulate the switching action of OT coil current of ADITYA Pulsed Power Supply (APPS) and LV by incorporating different electrical switches and resistance values.

All the electrical components are assembled to realize the wave shaping circuit OT coil of ADITYA-U Tokamak as shown in Fig. 4. To realize the operation of the OT power supply with peak current, energy is stored in the inductor (OT coil) in the form of current. To incorporate the OT current switching action, three resistors of different magnitudes along with the time-controlled switches are connected in series with ohmic coil; resistance and inductance are 90 mΩ and 16.4 mH, respectively. Switching resistances value, resistance switching time and inductance of primary circuit are the inputs of model and can be configured easily according to the operational parameters of the ADITYA-U tokamak. Electrical-Model is validated with MATLAB-Simulink for the same input parameters. Ohmic coil current (Fig. 8) and loop voltage (Fig. 9) are generated by this MATLAB-Simulink circuit which are having the profiles of ohmic current and LV which match with the profiles generated by Electrical-Model.

Detailed circuit of the OT wave shaping circuit is shown in Fig. 7, and OT current is generated by MATLAB-Simulink as shown in Fig. 8.

LV generated by Electrical-Model is validated with MATLAB-Simulink results as shown in Fig. 9, and a very good matching has been achieved between the two.

This model can be used to predict different magnitudes of LV by incorporating different sets of resistance and at different ignitron switching times.

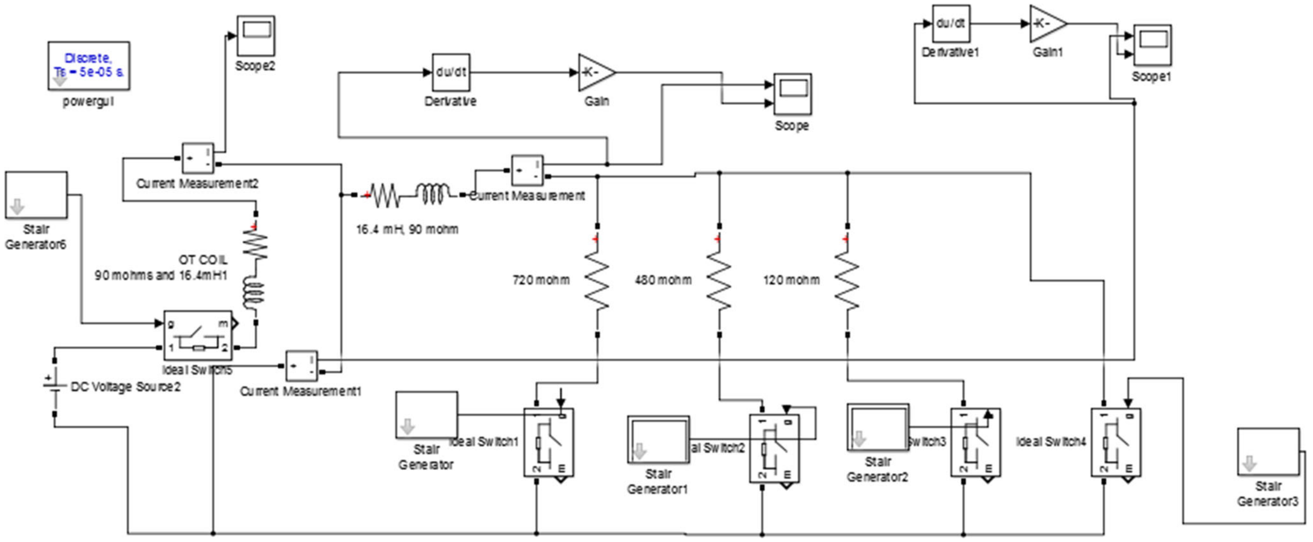

Fig. 7 OT wave shaping circuit in MATLAB-Simulink

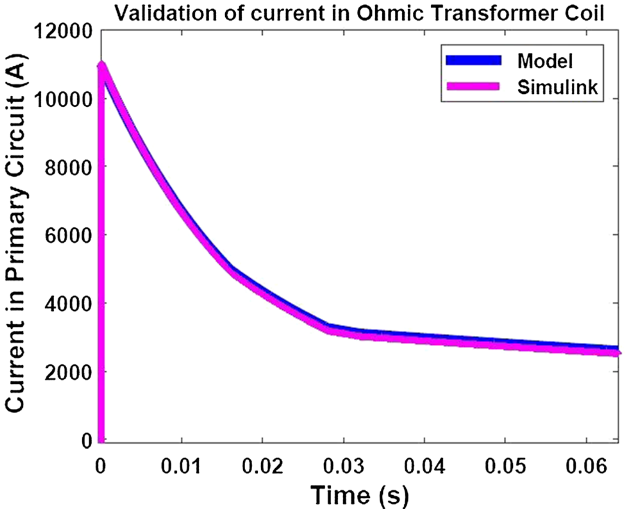

Fig. 8 Validation of primary current for a typical vacuum shot #31868

3. Results and discussions

3.1. Profile of loop voltage

Modelling of LV for ADITYA-U plasma discharge is performed to control the rate of rise, impurity burn-through phase and flat-top duration of the plasma current. Time-varying OT current has been developed by Electrical-Model to obtain the required value of LV to control the plasma current parameters. OT coil current is responsible for the shape of LV. In order to generate LVs for the vacuum discharges where plasma is absent, Eq. 2 has been used. After third resistance switching time, 90 mΩ resistance value of OT Coil is considered in LV generation circuit (Fig. 4) in order to generate all LV profiles.

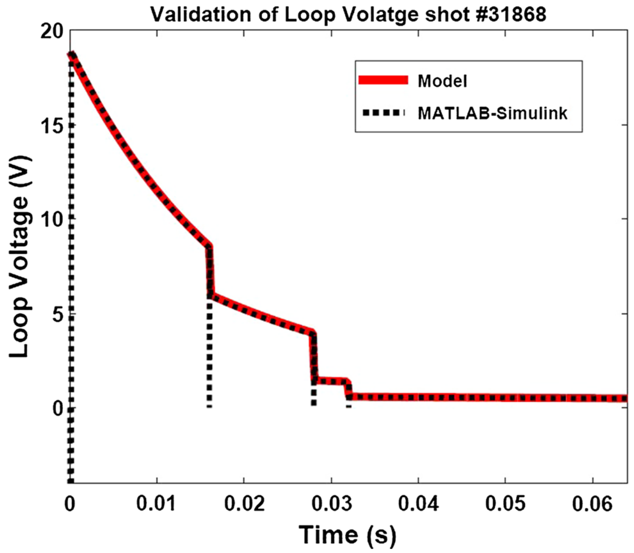

Fig. 9 Validation of loop voltage for a typical vacuum shot #31868 using MATLAB-Simulink

For ADITYA-U discharges, validation of Modelled LV is performed with the experimentally measured vacuum discharges (without gas) for discharge #31555 and #32036. These discharges are shown in Figs. 10 and 11, and its input parameters are given in Tables 2 and 3, respectively. A good agreement is observed between the two within the experimental tolerance.

Mutual coupling factors between OT coils and plasma column are obtained from the inductance matrix of the ADITYA-U Tokamak [9].

Time traces of plasma loop voltage is given by Eq. 7, and mutual inductance M_2 is define by Eq. 8.

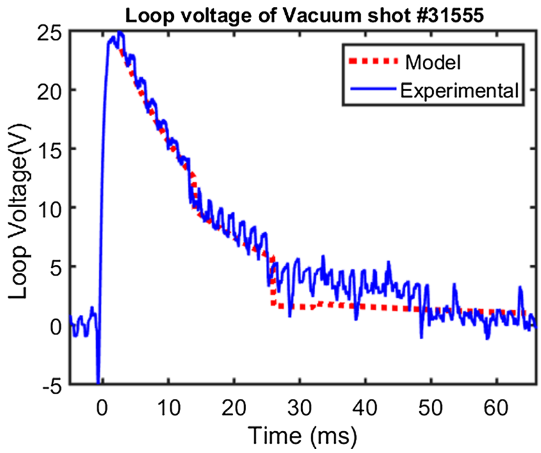

Fig. 10 Validation of modelled loop voltage with experimental vacuum discharge #31555

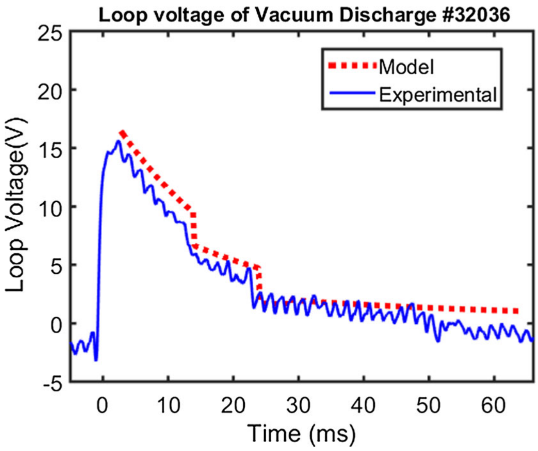

Fig. 11 Validation of modelled loop voltage with experimental vacuum discharge #32036

Table 2 Wave shaping circuit parameter for discharge #31555

Initial time (ms)	Resistance switching time (ms)	Resistance value (mΩ)
0	14	*R*1 = 840
14	26	*R*2 = 640
26	32	*R*3 = 120

Table 3 Wave shaping circuit parameters for discharge #32036

Initial time (ms)	Resistance switching time (ms)	Resistance value (mΩ)
0	14	*R*1 = 720
14	24	*R*2 = 480
24	28	*R*3 = 120

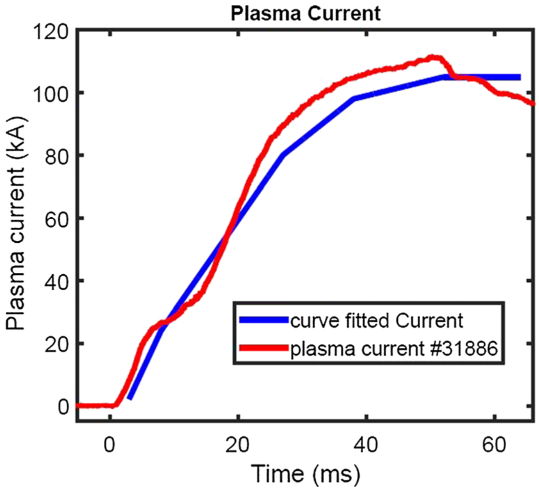

Fig. 12 Assumed temporal profile of plasma current

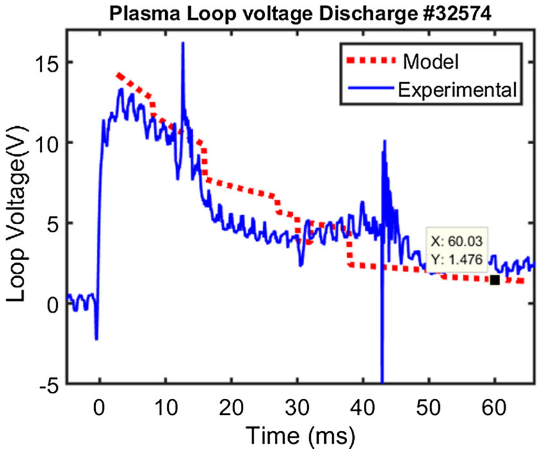

Fig. 13 Comparison of modelled loop voltage with experimental discharge #32574

$$VL_{\mathrm{p}} = VL_{\mathrm{Vac}} + M_2 \frac{\mathrm{d}I_{\mathrm{p}}}{\mathrm{d}t} \tag{7}$$

$$M_2 = K\sqrt{L_{\mathrm{OT}} L_{\mathrm{p}}} \tag{8}$$

where K is constant,

$$L_{\mathrm{p}} = L_i + L_{\mathrm{ext}} \tag{9}$$

where L_{p} denotes the total plasma inductance in Eq. 9, and L_i = 0.5 µH [11] and L_{ext} = 1.001 µH [12] are internal and external inductances of plasma, respectively. I_{p} is the plasma current, and M_2 is the mutual inductance between plasma secondary ring and flux loop. LV_{vac} is a vacuum discharge LV defined by Eq. 2. Loop voltage results for a typical plasma discharges are also taken and compared with the Electrical-Model result as shown in Figs. 13 and 14. Modelled loop voltages by Electrical-Model are matching quite well with the experimental LV for plasma shots #32574 and #32046 while having different inputs.

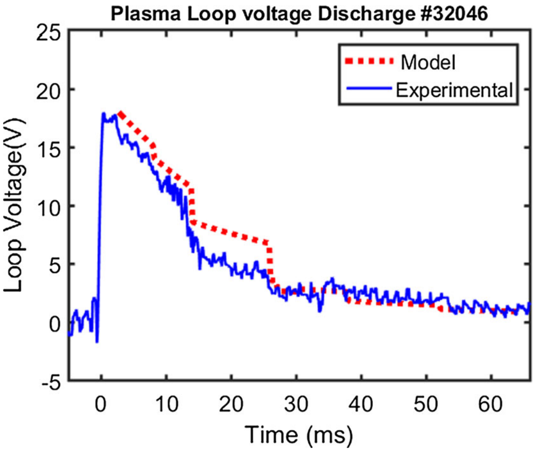

Fig. 14 Comparison of modelled loop voltage with experimental discharge #32046

Table 4 Wave shaping circuit parameters for discharge #32574

Initial time (ms)	Resistance switching time (ms)	Resistance value (mΩ)
0	16	$R1 = 360$
16	30	$R2 = 240$
30	38	$R3 = 120$

Table 5 Wave shaping circuit parameters for discharge #32046

Initial time (ms)	Resistance switching time (ms)	Resistance value (mΩ)
0	16	$R1 = 720$
16	28	$R2 = 480$
28	32	$R3 = 120$

After matching loop voltages for vacuum discharges, the modelled LV is compared with experimental results for different plasma discharges in ADITYA-U Tokamak. The plasma response is included in LV through second term of right side of Eq. 7, and curve fitted plasma current (Fig. 12) by experimental data is used to generate plasma LV in timescale between 0 and 64 ms.

The modelled and experimentally measured LVs are compared in Figs. 13 and 14 for input parameters as shown in Tables 4 and 5, respectively, which shows reasonably good match between the two.

4. Conclusion

Electrical-Modelling of any tokamak system helps in the prediction of operational parameters towards the optimized experimental results. An Electrical-Model of ADITYA-U Tokamak machine is developed to describe the transformer action of tokamak. Electrical-Model for ADITYA-U Tokamak has been designed and implemented in the Electrical-Model.

Different output parameters have been modelled for the ADITYA-U Tokamak. OT current has been fabricated to develop the desired shape and magnitude of the LV. This LV generation circuit has been modelled in Electrical-Model by varying the resistance and ignitron switching values, and validated with ohmic wave shaping circuit in MATLAB-Simulink for vacuum discharges. LV profiles obtained from the model matches well with those measured experimentally.

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References

[1] G Mc Cracken and P Stott *Fusion: The Energy of The Universe*, 2nd Edn. (London: Academic Press) (2013)
[2] J Wesson "*Tokamaks*" Chapter 2 (1987)
[3] J P Freidberg *Plasma Physics and Fusion Energy* (Cambridge University, Cambridge) (2010)
[4] J A Romero and JET-EFDA Contributors *Nucl. Fusion* **50** 115002 (2010)
[5] V S Mukhatov and V D Shafranov *Nucl. Fusion* **11**, No. 6 (1971)
[6] J Ghosh, R Tanna, S B Bhatt, P K Chattopadhyay, K Sathyanarayana, C Chavda et al *Upgrade of ADITYA Tokamak with Limiter Configuration to ADITYA Upgrade Tokamak with Diverter Configuration* IAEA Fusion Energy Conference (Kyoto), FIP/P4-46 (2016)
[7] R L Tanna, J Ghosh, Raj Harshita, Rohit Kumar, Suman Aich, Vaibhav Ranjan et al *Plasma Sci. Technol.* **20** 074002 (2018)
[8] M A Lieberman and A J Lichtenberg *Principles of Plasma Discharge and Material Processing*, 2nd edn. Chapter—Direct Current (DC) Discharges
[9] S B Bhatt, D Bora, N N Buch, C N Gupta, K K Jain, R Jha, et al *Indian J. Pure Appl. Phys.* **27** 710 (1989)
[10] B K Shukla, J Patel, H Mistry, H Patel, D Purohit, K G Parmar, et al *Fusion Eng. Device* **03** 108 (2019)
[11] A Salar Elahi and M Ghoranneviss *J. Fusion Energy* **29** 76 (2010)
[12] J H Malmberg and M N Rosenbluth *Rev. Sci. Instrum.* **36** 1886 (1965)

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